VENUS NOW AND THEN. Roger J. Phillips, *Department of Earth and Planetary Sciences, Washington University, St. Louis MO 63130, USA, phillips@wustite.wustl.edu*, Vicki L. Hansen, *Department of Geological Sciences, Southern Methodist University, Dallas TX 75275, USA*.

Introduction

The tectonic and magmatic evolution of Venus can be understood if there was a switch in convective style from a mobile lid to a sluggish lid regime [1,2,3]. Because of a high surface temperature and thin lithospheric lid, massive amounts of partial melt can be generated from mantle upwellings in the mobile lid regime. We suggest that volcanic rises and crustal (highland) plateaus are both formed by rising mantle plumes but at distinctly different times in Venus history. Tesserae and crustal plateaus formed in the mobile lid regime; volcanic rises form in the sluggish lid regime. We base this hypothesis on four basic points: (*i*) The earliest tectonic phase observed in most tessera units is extensional in nature [4,5], suggestive of upwelling. (*ii*) Cratering evidence shows that crustal plateaus could be considerably older than volcanic plains - in fact their age appears to be not constrained at all other than that they must be older than the plains. (*iii*) Observations imply that the lithosphere of Venus is relatively thick today [6]. There is the notion that it was much thinner in the past [4]. (*iv*) It has been argued that the formation of crustal plateaus by subsolidus flow in the crust over mantle downwellings [7] is mechanically implausible [8], given dry diabase rheology [9].

We suggest that the switch from mobile to sluggish lid convection caused rapid thickening of the thermal lithosphere, which in turn shut off partial melting. Subsequent reheating of the interior eventually led to modest partial melting and the emplacement of volcanic plains over an interval of ∼0.5 Ga, commencing at about 1 Ga [10]. The stress state of the lithosphere evolved from compressional to tensional, leading to the present tectonic regime of rifting, coronae, and constructional volcanism. Below we discuss various aspects of this hypothesis.

Geological Constraints

Hansen and Willis [4,5] have documented that the oldest preserved tectonic fabric ("ribbon terrain") on the tesserae of crustal/highland plateaus records large amounts (50-100%) of extension. Contractional deformation follows in time, and the last phase of tectonics is one of normal fault/graben formation. These observations reinvigorate the hypothesis that crustal plateaus formed as a result of upwelling/magmatic processes [11, 12, 13]. Craters on tessera terrain are deformed only by the last (graben) stage of tectonics [14]. It seems clear that crater counts on crustal plateaus yield only a retention age, and that plateau formation itself *could* be quite ancient.

Switch in Convective Style

The state of crustal stress relative to crustal yield strength in models of mobile lid convection was used to evaluate theories regarding the change of convective style on Venus. In particular, we asked whether Venus passed from a mobile lid to a sluggish lid regime because stress decreased below a critical value for lithospheric failure [1]. In a mobile lid regime (∼ constant viscosity), maximum crustal deviatoric stress (square root of second deviatoric stress invariant; approximately independent of depth in crust) in finite element runs was tabulated as a function of Rayleigh number, Ra, in lithospheric models subject to basal normal tractions [8]. The results were parameterized, and maximum crustal stress, σ_{max}, is well represented by the relationship $\sigma_{max} = 123[\mathrm{Ra}/\mathrm{Ra}_{\mathrm{ref}}]^{2.22}$, where the reference Rayleigh number, $\mathrm{Ra}_{\mathrm{ref}}$, corresponds to an approximately Chondritic mantle at 1 Ga (heat flux of 50 mW m^{-2} into a 50-km-thick thermal lithosphere). We used the evolving Rayleigh number in a parameterized convection model run to generate a time-dependent σ_{max}. For a specific Rayleigh number, the yield strength envelope of the crust can also be calculated; as expected, the brittle-plastic transition (BPT) migrates upward with increasing Rayleigh number, decreasing the yield stress, σ_{BPT}, at the BPT. The ratio $\sigma_{max}/\sigma_{BPT}$ is a strong function of the Rayleigh number, varying approximately as Ra^3. In Figure 1, we show this ratio as a function of age for a specific parameterized convection model run. At 1 Ga, the ratio is 0.25, but by ∼ 2.5 Ga, the ratio has exceeded unity. We realize that the BPT stress may overestimate the strength of the crust [15]; if the actual strength is a fraction of σ_{BPT}, then the curve in Figure 1 would simply be shifter upward.

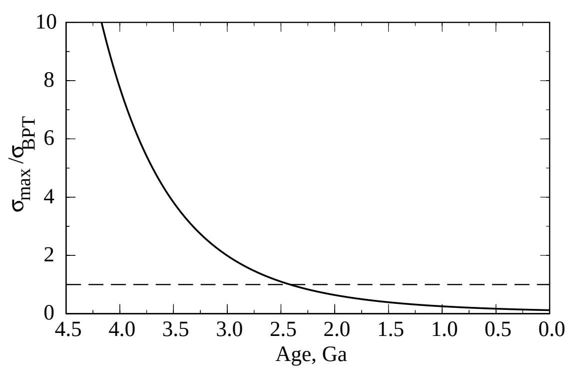

Figure 1. Ratio of maximum crustal deviatoric stress to stress at brittle-plastic transition as a function of age.

Presumably, Venus could transition from a mobile to a sluggish lid regime when $\sigma_{max}/\sigma_{BPT}$ drops below unity. Other possibilities for this transition are loss of negative buoyancy of the lithosphere as the crust thickens [3,16], and loss of volatiles from the lithosphere [17].

Magmatic Consequences

We examined the magmatic consequences of this solution by calculating the partial melt fraction as a function of time. We stipulated that plumes, with an excess temperature of 200 K, thermally penetrate the bottom third of the thermal lithosphere. The melting relationships given by McKenzie and Bickle [18] were used to calculate the percentage of partial melt as a function of age. Figure 2 shows one result, where the switch from mobile to sluggish lid takes place at 2 Ga. These curves show the $P-T$ paths for melting as a function of age. Prior to the switch, the lithosphere is quite thin (3/2 the minimum melting depth). Subsequent to the switch, the lithosphere thickens rapidly by diffusion; it then reaches a quasi-equilibrium thickness from the competing effects of cooling and basal heat flux. During the mobile lid phase, sufficient partial melt is generated to create crustal plateaus. At the onset of the stagnant lid, the thickening lithospheric lid shuts off partial melting (a 30 km lithosphere thickens to $\sim$ 120 km in about 0.5 Gyr; this latter value is consistent with gravity modeling [6]). But the interior also heats up, and by about 1 Ga, 5% partial melt can be generated in the mantle. Eruption of metastable accumulations of melt could then lead to the widespread plains emplacement.

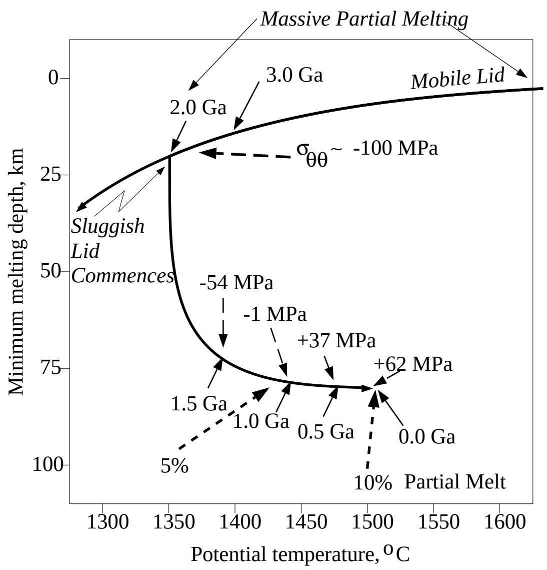

Figure 2. Evolutionary $P-T$ paths for mobile and sluggish lid convection regimes. Lithospheric horizontal normal stress, $\sigma_{\theta\theta}$, is indicated along with fraction of partial melt generated in sluggish lid regime.

Tectonic Consequences

Figure 2 also shows lithospheric horizontal normal stress at several ages. This stress arises from thermoelastic effects in the lithosphere and membrane effects induced by cooling or heating of the interior. During the approximately first Gyr after commencement of the sluggish lid, the lithosphere is in compression. We propose that this is the environment of the occasional voluminous eruptions that lead to the plains. Subsequently, the stress becomes tensional, leading to the present environment of rifting and constructional volcanism, and a more continuous but smaller rate of eruption. It is also possible that with an immobile lithospheric lid, accumulating melt residuum is relatively stable; this would lead to a decrease in partial melting fraction with time [19].

The thickening of the lithosphere also leads to a dramatic increase in the brittle-plastic transition depth. This could explain why early crustal plateaus collapsed into the lowlands, leaving only vestiges of their existence, while the last of the crustal plateaus were left highstanding.

Conclusions

The main point of this model is to investigate the tectonic and magmatic consequences of a Venus that switches from a mobile lid to a sluggish lid regime at some time in its past. Tessera and crustal plateaus are products of the former regime; plains emplacement and rifts/corona/constructional volcanism are associated with the latter. In particular, we believe that volcanic rises are the magamatically "dry" and (relatively) thick lithosphere equivalents of crustal plateaus.

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